福山大学工学部紀要
第30巻 2006年12月

CONTROL OF TRAFFIC FLOW DYNAMICS IN A TWO-WAY TRAFFIC NETWORK

Hikaru Shimizu* , Masa-aki Kobayashi**,Haruko Fujii*** ,
Hiroshi Ishikawa*, Kazuo Kawakubo* and Toshio Shintani*

*Department of Information Processing Engineering
**Department of Mechanical System Engineering
***Department of Information Science and Technology
Yuge National College of Maritime Technology

ABSTRACT

This paper studies a control of traffic flow dynamics in a two-way traffic network. The signal control system of the congestion length is described by a nonlinear time-varying discrete dynamic system and synthesized by using the hierarchical control. A signal control algorithm in which the three signal control parameters consisting of the cycle length, green split and offset are searched systematically so as to minimize the sum of congestion lengths in a two-way traffic network is presented. The dynamic route guidance system is consisted of both the evaluation for the mean OD travel time and the route search algorithm. The integrated traffic flow control system, which is most effective to reduce the congestion lengths in a two-way traffic network, is designed by connecting the signal control system with the dynamic route guidance system in real time.

Keywords: traffic flow dynamics, signal control system, dynamic route guidance system, integrated traffic flow control system.

1. INTRODUCTION

Automobiles play the most important role in transportation systems in Japan. In recent years, along with the increase of registered automobiles, the congestion has increased in urban road networks in Japan. The congestion has caused problems such as the increase of the travel time, exhaust pollutions and fuel consumption. In order to solve the congestion of traffic networks, the signal control system and the dynamic route guidance system have been developed using a real time control.

Since incoming volumes and queue lengths at each signalized intersection increase rapidly in rush hours, the three signal control parameters are desired to be controlled not independently but systematically to optimize the performance criterion. In this paper, the three signal control parameters are controlled systematically and sequentially according to variations of incoming volumes, queue lengths and running speeds (Ishikawa, et al., 2003).

A dynamic route search algorithm which plays an essential role in the dynamic route guidance system is presented. The algorithm gives theoretically the shortest mean OD travel time route of the urban road network using the Dijkstra's algorithm (Dijkstra, 1959) weighted by the mean link travel time. The mean OD travel time from the driver's origin to his destination is evaluated by summing up the mean link travel time along the route.

Finally, the integrated traffic flow control system, which is most effective to reduce the congestion lengths in urban road networks, is designed hierarchically by connecting the signal control system with the dynamic route guidance system in real time.

2. SIGNAL CONTROL SYSTEM

2.1 *Signal Control System*

In the volume balance at each signalized intersection, it is assumed that the incoming volume is measured by vehicle detectors and the outgoing volume is controlled by the three signal control parameters at the signalized intersection concerned

$$x_o(i,j,m,k) = f[c_y(i,j,m,k), r_g(i,j,m,k), t_{off}(i,j,m,k)] \quad (1)$$

where i,j and m denote the location of each signalized intersection and the approach of vehicles respectively (see Fig.1). Time is shown by $k=k\Delta T$, and $c_y(i,j,m,k)$, $r_g(i,j,m,k)$ and $t_{off}(i,j,m,k)$ denote the cycle length, green split and offset respectively. The control input $u(i,j,m,k)$ is defined by

$$u(i,j,m,k) \underline{\underline{\Delta}} f[c_y(i,j,m,k), r_g(i,j,m,k), t_{off}(i,j,m,k)] \quad (2)$$

The signal control system is then written by

$$\begin{cases} x_e(i,j,m,k) = x_e(i,j,m,k-1) \\ \qquad + x_i(i,j,m,k) - u(i,j,m,k) \\ y_c(i,j,m,k) = l_m(i,j,m,k) \cdot x_e(i,j,m,k) \end{cases} \quad (3)$$

where $x_e(i,j,m,k)$ denotes the excess incoming volume. The incoming volume in case of the congestion $x_i'(i,j,m,k)$ equals to $x_e(i,j,m,k-1)$ + $x_i(i,j,m,k)$. The observation equation of the congestion length $y_c(i,j,m,k)$ is described in such a way that the state variable is multiplied by a "transformation factor" $l_m(i,j,m,k)$.

The signal control system of the congestion length is considered in the traffic network; in this control system, the reference input, control input and output are given by the permitted congestion length $l_r(i,j,m,k)$, the three signal control parameters and the congestion length respectively. In this way, the signal control system of the congestion length is synthesized using the feedback control for any traffic flows at each signalized intersection. The purpose of the signal control system of two-way traffic networks is to find such control input that it makes the following performance criterion $J_n(k)$ minimize

$$J_n(k) = \sum_{i=1}^{L}\sum_{j=1}^{N}\sum_{m=1}^{4} g(i,j,m,k) \quad (4)$$

where L and N denote the number of signalized intersection along the direction for i and j. The function $g(i,j,m,k)$ and the control error $e(i,j,m,k)$ are defined by

$$g(i,j,m,k) \underline{\underline{\Delta}} \begin{cases} 0 & e(i,j,m,k) \geq 0 \\ |e(i,j,m,k)| & e(i,j,m,k) < 0 \end{cases} \quad (5)$$

$$e(i,j,m,k) \underline{\underline{\Delta}}\, l_r(i,j,m,k) - y_c(i,j,m,k) \quad (6)$$

because degrees of saturation are different to approaches at signalized intersections.

2.2 *Signal Control Algorithm*

The signal control of the congestion length in a two-way traffic network means that the three signal control parameters are controlled systematically and sequentially so as to minimize the performance criterion of the traffic network described by Eq. 4, under such a constraint that the sum of the green time, yellow time and offset at each signalized intersection in a closed link equal to n times of the common cycle length. We call this control algorithm as the network control algorithm (Ishikawa, et al., 2003).

2.3 *Simulation Results.*

The network control algorithm of the congestion length for a two-way traffic network is simulated at twelve signalized intersections during morning and evening rush hours in Fukuyama

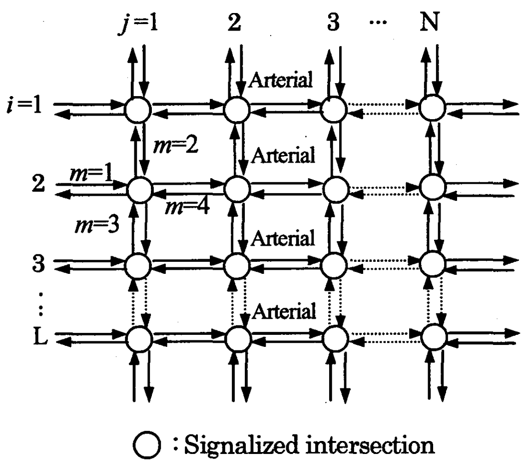

Fig.1. Two-way traffic network consisting of a rectangular grid of intersecting streets.

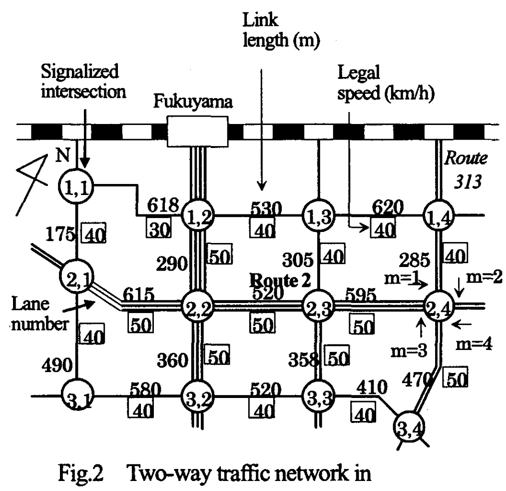

Fig.2 Two-way traffic network in Fukuyama city

city(see Fig.2), Japan. The Phases, the parameters and the incoming volumes are arranged for the simulation at twelve signalized intersections based on measurement data. Serious oversaturated signalized intersections are four signalized intersections along the Route 2 from the viewpoint of the congestion length control in the traffic network.

The straightforward incoming volumes for each lane vary randomly cycle by cycle at signalized intersections. The incoming volumes increase suddenly during evening rush hours at three signalized intersections. The reference input is set as $l_r(i,j,m,k) = 0m$ for all approaches. In the network control algorithm, the green time defined by the product of the cycle length and the green split are searched to minimize the performance criterion of arterials. The cycle length is commonly controlled by the control algorithm at twelve signalized intersections according to variations of incoming volumes at such oversaturated signalized intersections that have the maximum values of the index $x_i'(i,j,m,k)$ / $c_x(i,j,m,k)$, where $c_x(i,j,m,k)$ denotes the capacity.

The balance offsets by Fieser's method are searched using the optimal values of the cycle length and the green split so as to maximize the through band width.

As the results, the congestion lengths of all approaches at twelve signalized intersections are controlled so as to minimize the performance criterion described by Eq.4. While congestion occur at nine signalized intersections in real circumstances (control by a pattern selection method), the congestion lengths are controlled to become nearly zero for all approaches at twelve signalized intersections by the network control algorithm. From the simulations, it is confirmed that the signal control system and the signal control algorithm work effectively for any topologies including single signalized intersection, arterials and traffic networks (see Fig.3).

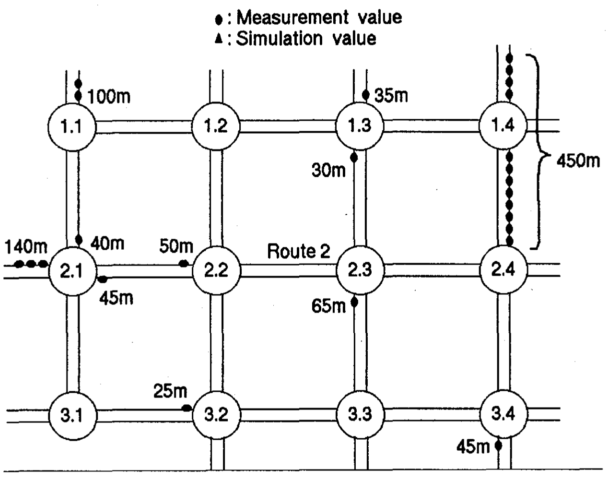

Fig.3 Comparison of congestion lengths for straightforward lane between simulation values and measurement values

3. DYNAMIC ROUTE GUIDANCE SYSTEM

3.1 *Evaluation of Link Travel Time.*

The mean link travel time of two-way traffic networks are analyzed by taking the congestion, offset control and moving direction of vehicles at downstream signalized intersections into account in this paper. The mean link travel time consisting of the running time and the stopping time are analyzed according to the classification of Fig.4. It is assumed that the cycle lengths and green splits are controlled optimally using a signal control algorithm.

A. In the Case of Non-Congested Traffic Flow at the Downstream Signalized Intersection

i) In the case of offset control

It is assumed that the offset is controlled for vehicles which run straightaway between two adjacent signalized intersections. The variables and subscripts used following equations are listed in Table1. Although the variables vary depending on the location and time, their subscripts i, j, m and k are omitted for simple descriptions in the right side of following equations. The mean link travel time is analyzed for moving directions at the downstream signalized intersection as follows:

In the case of straightaway

The running time $T_r(i,j,m,k)$ is analyzed by taking the link length, queue length and running speed into account.

$$T_r(i,j,m,k) = t_{run} \tag{7}$$

with

$$t_{run}(i,j,m,k) = (d - y_s)/v_s \tag{8}$$

The stopping time $T_s(i,j,m,k)$ is analyzed by taking the yellow time, red time and starting delay into account.

$$T_s(i,j,m,k) = P_s\{P_y(t_y/2 + t_r + t_s) + P_r(t_r/2 + t_s)\} \tag{9}$$

Traffic Flow	Offset Control	Moving Direction at Downstream Signalized Intersection
non-congestion	control	straightaway right-turn left-turn
	non-control	straightaway right-turn left-turn
congestion		straightaway right-turn left-turn

Fig.4 Classification for analysis of mean link travel time.

In the case of right-turn

The running time is analyzed by taking the straight running time and the outgoing time of right-turn lane queue.

$$T_r(i,j,m,k) = t_{run} + t_{cr} \tag{10}$$

with

$$t_{cr}(i,j,m,k) = q_r / 2\phi_r \tag{11}$$

The stopping time is analyzed by taking the time difference of green initiation between straightaway and right-turn directions.

$$T_s(i,j,m,k) = t_{dr} / 2 + t_s \tag{12}$$

In the case of left-turn

$$T_r(i,j,m,k) = t_{run} + t_{cl} \tag{13}$$

with

$$t_{cl}(i,j,m,k) = q_l / 2\phi_l \tag{14}$$

$$T_s(i,j,m,k) = t_{dl} / 2 + t_s \tag{15}$$

ii) In the case of non-offset control

Vehicles arrive at any traffic signals at the downstream signalized intersection. The detail of the analysis is referred to the paper (Shimizu, et al., 2000).

B. In the Case of Congested Traffic Flow at the Downstream Signalized Intersection

It is assumed that the signal is controlled optimally and drivers can not pass the downstream signalized intersection even if the traffic signal is green. The detail of the analysis is referred to the paper (Shimizu, et al., 2000).

The mean OD travel time from a driver's origin to his destination $T_{OD}(k)$ is evaluated by summing up each mean link travel time along the route

$$T_{OD}(k) = \sum_i \sum_j \sum_m (T_r(i,j,m,k) + T_s(i,j,m,k)) \tag{16}$$

3.2 *Route Search Algorithm.*

We propose a route search algorithm which plays an essential role in the dynamic route guidance system. An outline of the route search algorithm is given as follows:

Step 1. An automobile driver inputs his origin and destination from the input device equipped vehicle.

Step 2. The traffic information are inputted to evaluate the mean link travel time of recommendable routes.

Step 3. The mean link travel time is evaluated using the evaluation of link travel time mentioned in 3.1.

Step 4. The recommendable routes including the shortest mean travel time route from a driver's origin to his destination are obtained using the Dijkstra's algorithm weighted by the mean link travel time.

Step 5. The recommendable routes are outputted according to the shortness of mean OD travel time at the output device equipped vehicle.

3.3 *Simulation Results.*

The route search algorithm is simulated at twelve signalized intersections in Fukuyama city(see Fig.2), Japan. The necessary traffic information such as the signal control parameters, starting delays, congestion lengths, running speeds, saturation flows etc. are arranged for the simulation.

From the simulation results of the route search algorithm, the

Table 1 Notation

t_{run}	Running time
t_y	Yellow time
t_r	Red time
c_y	Cycle length
p_s	Stopping rate at the downstream signalized intersection
p_y	Probability of yellow time given by t_y/c_y
p_r	Probability of red time given by t_r/c_y
t_{dr}	Time difference of green initiation between straightaway and right-turn directions
t_{dl}	Time difference of green initiation between straightaway and left-turn directions
t_{cr}	Outgoing time of right-turn lane queue
t_{cl}	Outgoing time of left-turn lane queue
t_s	Starting delay
q_r	Queueing number of vehicles of right-turn lane
ϕ_r	Saturation flow on the approach of right-turn lane at the downstream signalized intersection
d	Link length
y_s	Queue length of straightaway lane
v_s	Running speed of straightaway lane

best routes for each time interval(see Table 2) are such that they avoid the arterial (Route 2) and are lesser number of right-turn and left-turn (see Fig.5). These dynamic route information are more useful than those given by the VICS.

4. INTEGRATED TRAFFIC FLOW CONTROL SYSTEM

4.1 *Integrated Traffic Flow Control System*

The integrated traffic flow control system, which is most effective to reduce the congestion lengths in two-way traffic networks, is constructed by connecting the signal control system with the dynamic route guidance system in real time (see Fig.6).

4.2 *Traffic Flow Control Algorithm*

The control algorithm of the integrated traffic flow control system is described as follows:

Step 1. The parameters and initial conditions of the integrated traffic flow control system are set at first.

Signal control system

Step 2. The measurement values of the queue lengths, running speeds and volumes obtained by vehicle detectors are inputted into the signal control algorithm.

Step 3. The three signal control parameters are searched so as to minimize the sum of congestion lengths in a two-way traffic network. The optimal signal control parameters and the measurement data obtained by vehicle detectors are inputted into the file system.

Step 4. The traffic signals are controlled by using the optimal signal control parameters, and the sum of congestion lengths are minimized in a two-way traffic network. Congestion lengths are outputted at variable signs.

The process from Step 2 to Step 4 are always performed by the sampling period ΔT.

Dynamic route guidance system

Step 5. An automobile driver inputs his origin and destination from the input device equipped vehicle.

Step 6. The recommendable routes obtained using the route search algorithm are outputted at the output device equipped vehicle. Major mean OD travel time are outputted at variable signs.

Table 2 Time Interval

Symbol	Time Interval	Number of Runs
A	7:30 ～ 9:00	10
B	9:00 ～11:00	10
C	11:00 ～13:00	10
D	13:00 ～15:00	10
E	15:00 ～17:00	10
F	17:00 ～19:00	10

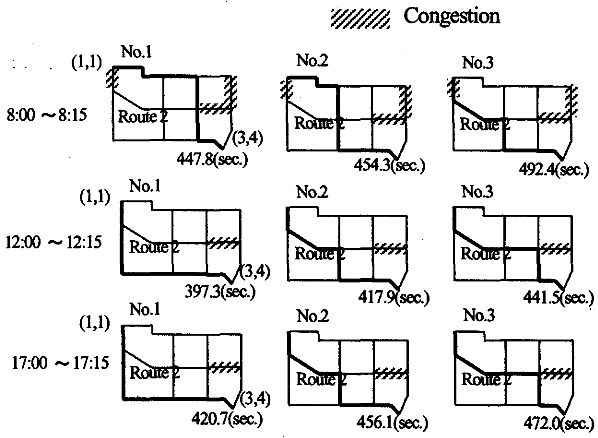

Fig.5 Recommendable routes searched by route search algorithm in each duration

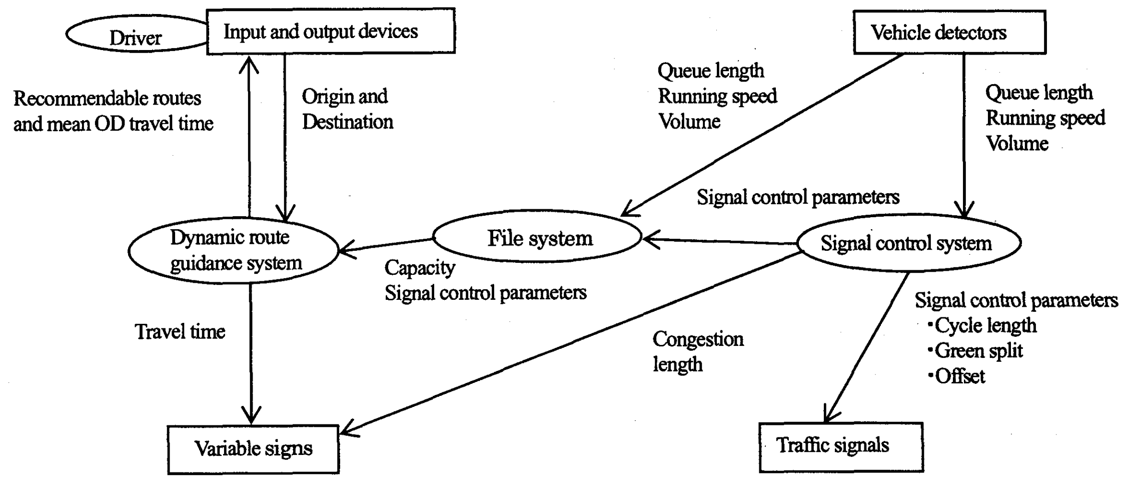

Fig.6 Integrated traffic flow control system

Step 7. The driver selects his route from the recommendable routes.

The process from Step 5 to Step 7 are performed only when drivers require the recommendable routes from the integrated traffic flow control system.

5. CONCLUSIONS

The integrated traffic flow control system consisting of the signal control system and the dynamic route guidance system is presented for a two-way traffic network in this paper. The following have been shown.

i) The traffic flow dynamics are described by a nonlinear time-varying discrete dynamic system based on the volume balance at each signalized intersection.

ii) The signal control system works well to minimize the performance criterion for any both traffic flows and topologies of traffic networks.

iii) The dynamic route guidance system outputs the recommendable routes at the output device equipped vehicle according to the shortness of mean OD travel time.

iv) The integrated traffic flow control system is designed by connecting the signal control system with the dynamic route guidance system in real time.

The simulations for both the integrated traffic flow control system and its algorithm are required in order to consider the effectiveness and problems in a two-way traffic network.

REFERENCES

1) Ishikawa,H. et al. (2003). Congestion control system in urban road networks. Preprints of the 10th IFAC Symposium on Control in Transportation Systems, pp 247-252.

2) Dijkstra, E.W. (1959). A note on two problems in connexion with graphs. Numerische Mathematik, 1, pp 269-271.

3) Shimizu,H et al. (2000). An analysis of mean link travel time for urban traffic networks. 2000 IEEE 51st Vehicular Technology Conference Proceedings, pp 318-322.